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The measurement of sound diffusion index in small rooms

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RESEARCH DEPARTMENT

THE MEASUREMENT OF SOUND DIFFUSION INDEX IN SMALL ROOMS

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Research Department Report No. **1969/16**

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THE MEASUREMENT OF SOUND DIFFUSION INDEX IN SMALL ROOMS

SUMMARY

Three methods of measuring sound diffusion are described. One is derived from the curvature of sound decay curves and a second is based upon the variation of reverberation time with position. Both these yield useful indices of diffusion and are suitable for automatic analysis with the aid of a computer. A third method, using a rotating directional microphone, was found to be valueless for small rooms of moderate absorption, although it is reported to yield a useful index for large or very reverberant rooms.

1. INTRODUCTION

A sound field is said to be diffuse if:

(a) there is uniform sound energy density within the region considered, and

(b) there is equal mean energy flow in all directions at any point in the field.

In the derivation of reverberation-time formulae, a diffuse sound field is assumed and sound absorption coefficients must, strictly, be measured in a reverberation room in which the sound field is diffuse. However, current interest in diffusion measurement does not arise only from concern about the theoretical basis of reverberation time and the accurate measurement of absorption coefficients. The main reason is that certain acoustical defects in a room, e.g. flutter echoes, are associated with concentrations of sound energy in specific directions and that such defects can be cured by taking steps to scatter the energy more uniformly.

Even now, reverberation-time and its variation with frequency are the only widely accepted objective criteria for the quality of a room; they are also widely recognized as necessary but not sufficient criteria. It has often been remarked that two rooms having the same reverberation-time/frequency characteristic can sound surprisingly different; the determination of an index characterising the state of diffusion of the sound field in a room appears to be the next and, perhaps, the final step in establishing satisfactory objective criteria.

There are two difficulties about basing measurement techniques on the definition of diffusion.

The first, a practical one, is that means of measuring sound energy and sound energy flow are not generally available. Microphones respond to sound pressure, sound pressure-gradient or a linear combination of these. While there are simple relations between sound pressure and energy density for the fields due to plane and spherical waves, in general no definite relations exist for the types of non-diffuse sound field found in rooms. The second difficulty, a theoretical one, arises from the fact that only the ideal state of perfect diffusion is defined quantitatively.

Departures from the state of perfect diffusion can arise from inhomogeneity in the sound energy density and from anisotropic energy flow, so that a true measure of diffusion might involve two independent parameters. It is not surprising that most investigations into the measurement of sound diffusion have been based on empirical approaches, using parameters related only indirectly to the basic attributes of a diffuse field. Most of these parameters are unsatisfactory measures of diffusion in practice either because they are difficult to evaluate or because they are too insensitive. Others are applicable only to large rooms and are of limited value to a broadcasting authority having a large number of talks, interview and discussion studios.

A practical study of sound diffusion in small rooms was made by Randall and Ward.[1] They varied the surface distribution of absorbents and also used a number of disposable solid shapes which were attached to the walls and floor to scatter the sound on reflection. Parameters indicating the state of diffusion were derived by examining certain characteristics of the reverberation decay-curves. Useful though these parameters were, the time taken to evaluate them discouraged their general use. However, with the development of automatic reverberation time measurement,[2] it was decided to investigate whether indices of diffusion based on the work of Randall and Ward could be obtained automatically from the digital decay data on punched paper tape. Two parameters appeared promising:—

(i) P, a quantity representing the variation of slope of the decay curves with microphone position, was the standard deviation of the reverberation time, obtained from warble tone pulses, at 15 microphone positions in the room. It was calculated at seven frequencies from 500 Hz to 8 kHz and was found to vary markedly with changes in the distribution of absorbents.

(ii) S, a quantity related to the curvature of a decay curve, was the ratio of the slopes of the upper and lower halves of the decay curve. It was regarded as the most suitable criterion to be adopted for routine diffusion measurements in operational studios.

2. EXPERIMENTAL PLAN

Randall and Ward showed that the state of diffusion could be controlled by a suitable distribution of absorbents over the surfaces of the room. Six different arrangements of absorbers were set up, in the experimental studio, which, from past experience, would be expected to cover the range of states of diffusion encountered in broadcasting practice. For each room condition, digital decay data on punched paper tape were obtained from the test recordings used in automatic reverberation time measurement.[2] With suitable programming the paper tapes were then processed in a computer to yield parameters closely associated with P and S.

In view of the complicated nature of diffusion it seemed likely that the two new computer-derived indices would not, at best, give precisely the same rank order for the six states of the room. At worst, they might not be capable of distinguishing the states of the room at all. As a check, it was decided to assess the states of the room by an independent method involving the use of a directional microphone.

3. THE SIX STATES OF THE ROOM

The experimental studio has the dimensions 6·7m x 4·9m x 3·4m. The six different distributions of absorbents are shown in Fig. 1; for all conditions other than F there was a woolcord carpet with underfelt covering the floor. The absorbent surfaces consisted of a combination of low-frequency, mid-frequency and high-frequency absorbers in modular sections, of dimensions 1·22m x 0·61m, distributed evenly over each surface.

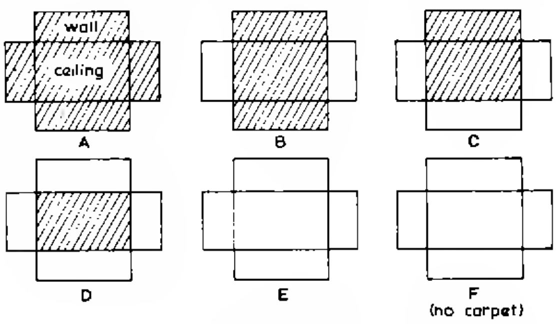


Fig. 1 - Distribution of absorbents for the six states of the experimental studio

Absorbent surface   Reflecting surface

The reverberation-time/frequency curve for each condition is shown in Fig. 2. Condition A would be acceptable for broadcasting purposes.

The ten microphone positions for the reverberation-time measurements, and hence for the modified P and S determinations, are shown in Fig. 3. The loudspeaker was a BBC Type LS5/5, pointed into a corner to reduce the level of the direct sound. An omnidirectional microphone was used.

4. THE MEASUREMENTS

4.1. Variation of Reverberation Time with Position

The computer printouts of reverberation time for the six conditions enabled the standard deviation of reverbera-

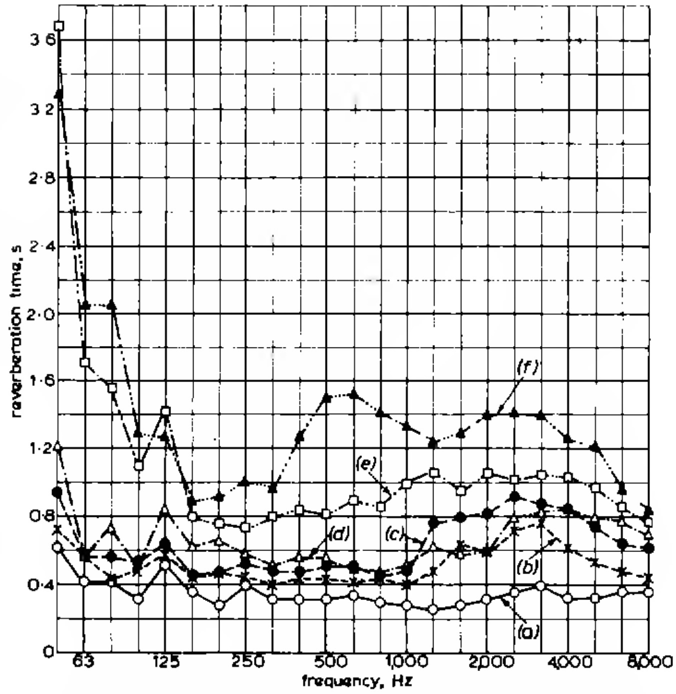


Fig. 2 - Reverberation times of experimental studio

(a) o——o	Condition A	(d) △—·—△	Condition D
(b) x---x	Condition B	(e) □·······□	Condition E
(c) ●— - ●	Condition C	(f) ▲———▲	Condition F

tion time at each frequency to be derived. When expressed as a percentage of the mean reverberation-time this gave the index P_c, closely related to Randall and Ward's P. P_c was obtained with 1/3 octave-bandwidth noise-excitation from 50 Hz to 8 kHz, at ten microphone positions, in contrast to P which was obtained with warble-tone excitation from 500 Hz to 8 kHz at fifteen positions.

The variations of P_c with frequency, for the different room conditions, are shown in Fig. 4.

Since the variation of P_c below 1 kHz appeared essentially random, the mean P_c for the 1/3 octave-bands between 1 kHz and 8 kHz was calculated for each condition and the results are shown in Table 1.

TABLE 1

Room Condition	A	B	C	D	E	F
P_c%	14	35	16	24	8	7

4.2. Curvature of Decays

First attempts to programme the computer to extract the index S from reverberation test-tape data produced absurd results. This arose from the difficulty of constructing an algorithm by which the 'upper half' and 'lower half' of a decay curve could be recognized. By dividing the dynamic range into two halves and programming the computer to run down the decay until the half-way level was exceeded, it was hoped that the mean reverberation-time above this point divided by the mean reverberation-time below, would yield the index S. Unfortunately, decay curves like that shown in Fig. 5 gave answers that were clearly wrong.

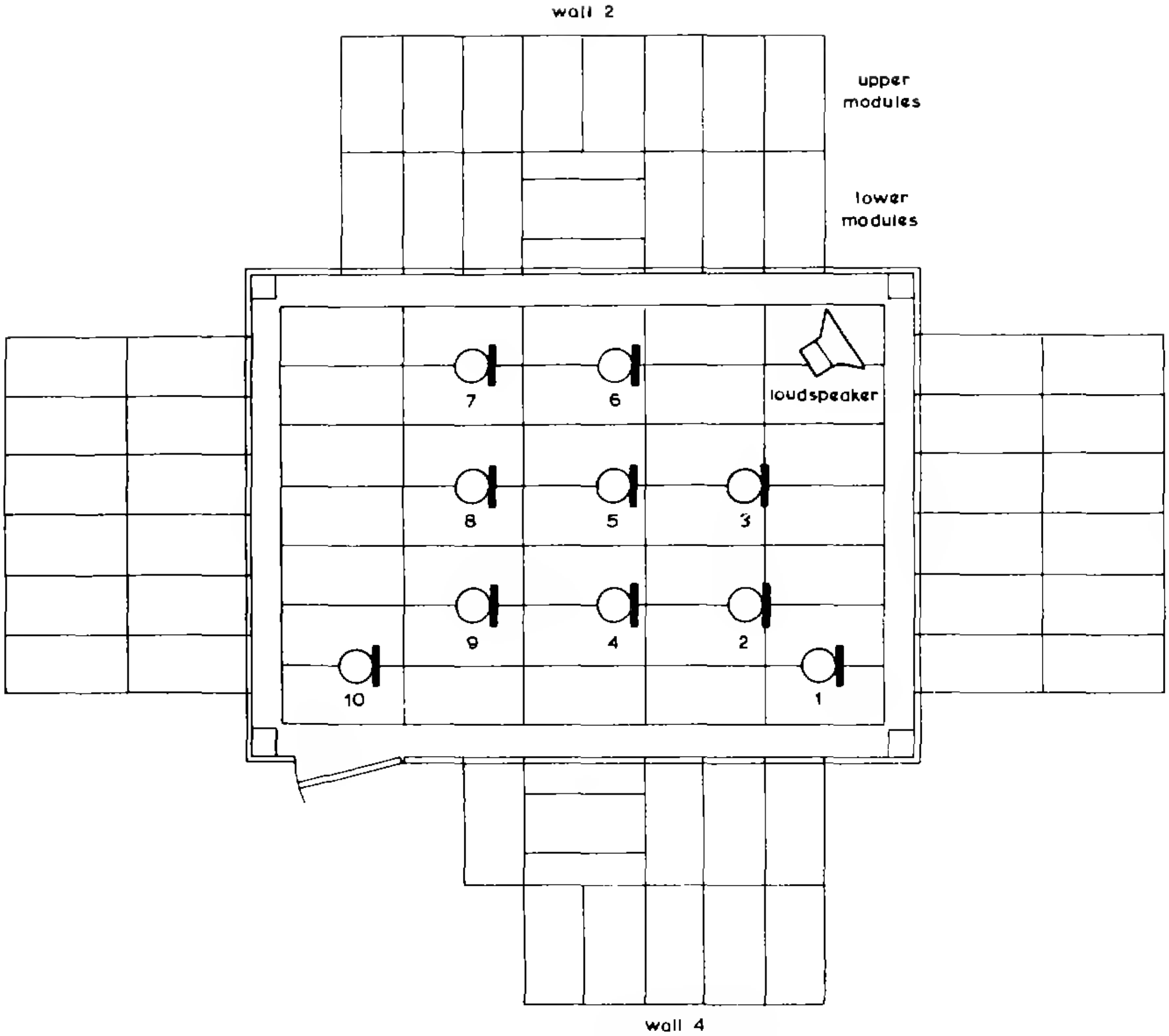


Fig. 3 - Microphone and loudspeaker positions

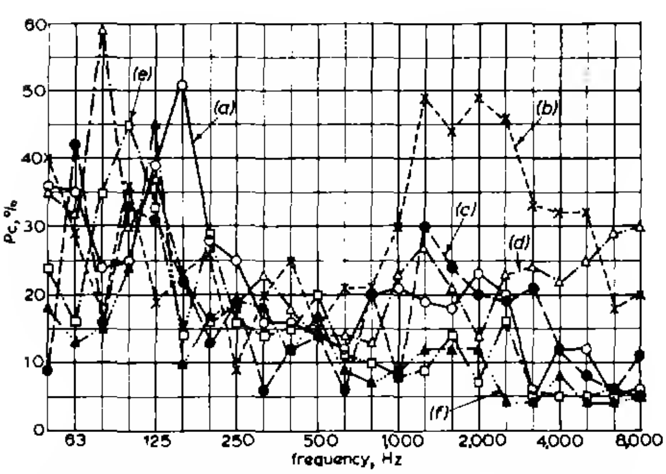


Fig. 4 - Variation of reverberation time with position, P_c

(a) o——o Condition A
(b) x- - -x Condition B
(c) ●- - -● Condition C
(d) △—·—△ Condition D
(e) □--·—·--□ Condition E
(f) ▲---—---▲ Condition F

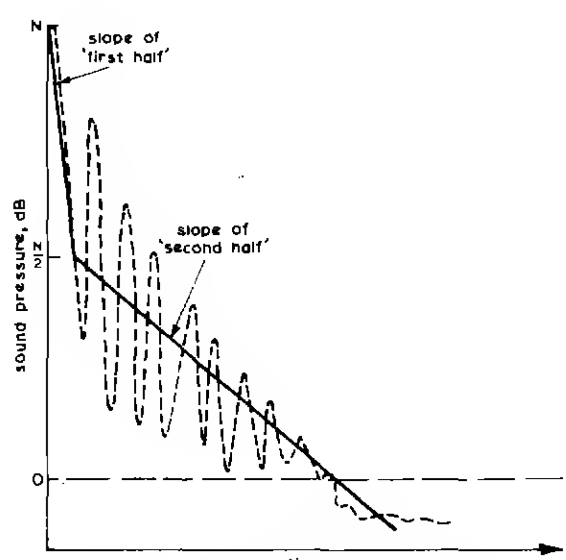


Fig. 5 - Anomalous measurement of S

Modifications to the definition of S were tried but they generally gave unreasonable answers with particular types of decay curve; that is, the indices derived were unsatisfactory because they were unduly sensitive to minor and acoustically unimportant characteristics of the decay curves.

Fortunately, one modification to S was found to be satisfactory in this respect. The computer was programmed to construct a line passing through the commencement of the decay curve (point A in Fig. 6), with a slope equal to the mean slope of the decay down to 6 dB above the noise level (point B in Fig. 6). The ratio of the area bounded by the real decay curve AB and the lines AC and BC, to the area of the triangle ABC was taken as a measure of the curvature of the decay curve. The resulting index, called S_A, was found to give results free from serious anomalies, presumably because minor characteristics of the curve make only a small contribution to the area under the curve.

The data used for deriving S_A was the same as that used for P_c.

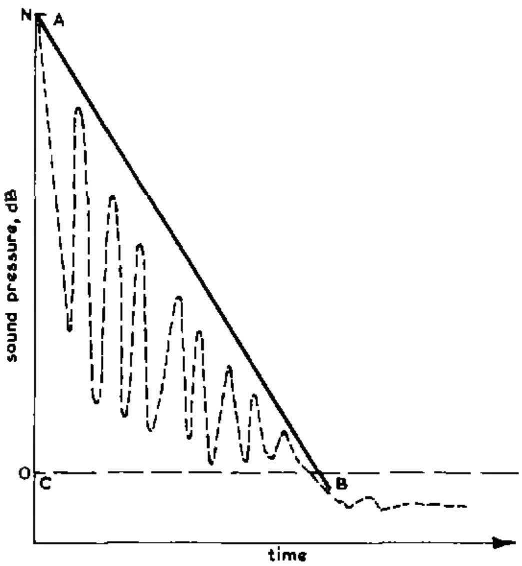


Fig. 6 - Measurement of S_A

It should be borne in mind that S differs from S_A in a number of ways: S was measured with pure tones and the results were averaged over twenty-six tone-bursts at 2 Hz intervals covering a band 25 Hz above and below the frequency of interest and at only one position in the centre of the room, whereas S_A was measured with noise of one-third-octave bandwidth at ten positions in the room. Whenever an individual reading of S exceeded unity the reciprocal of S was used in forming the mean of a set of readings, on the grounds that otherwise a set of convex and concave curvatures would tend to an average of unity. This procedure was not followed in the determination of S_A because it was felt that there is a greater danger that random errors in the measurement of S_A for a set of essentially straight decay curves would thereby be converted to systematic errors reducing the value of S_A to less than unity.

The results of the measurements of S_A in the experimental studio are shown in Fig. 7. As with P_c, there is little to distinguish the curves below 1 kHz. The mean S_A from 1 kHz to 8 kHz for each room condition is shown in Table 2.

TABLE 2

Room Condition	A	B	C	D	E	F
S_A	0·93	0·85	0·80	0·87	0·89	0·96

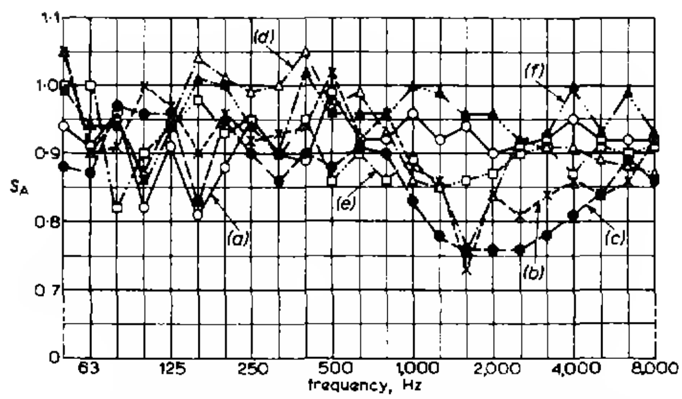


Fig. 7 - Curvature of decay curves, S_A

(a) o——o Condition A
(b) x– – –x Condition B
(c) ●——● Condition C
(d) Δ—·—Δ Condition D
(e) □-·-·-□ Condition E
(f) ▲···—···▲ Condition F

4.3. Directional Microphone Measurements

Meyer and others[3] working at Göttingen, have developed a method of measuring diffusion by examining the variation in the output of a highly directional microphone as it is rotated. While the method appears to have been successful for concert halls and other large rooms, it does not seem to have been applied to small rooms.

Early attempts by the authors' colleagues to adapt the method for small rooms were fruitless,* apparently meaningless results being obtained. Although a number of hypotheses for the failure were put forward, to have tested them would have been uneconomic in the circumstances then prevailing. Instead, a more promising method was investigated. Furduev and Ch'eng T'ung[4] have described a method whereby a directional microphone is rotated in a horizontal plane in a stationary noise field produced in the hall under consideration. The output of the microphone is plotted by means of a polar chart recorder, 0° corresponding to the direction of the loudspeaker. The measurement is then repeated in an anechoic chamber, the input to the chart recorder being adjusted so that the response at 0° is equal to that obtained in the hall.

In Fig. 8, $R(\theta)$ is the polar diagram obtained in the hall and $D(\theta)$ is the directional characteristic obtained in the anechoic chamber; in the figure they are both surrounded by a circle of radius equal to the forward response of the

* M.E.B. Moffat, L.M.B. Dyer and M.G. Croll devised most of the apparatus and carried out the early work.

microphone. The index of diffusion d is defined as:

$$d = \frac{A_1 - A}{A_1} \qquad (1)$$

where A_1 is the area bounded by the circle and $D(\theta)$ and A is the area bounded by the circle and $R(\theta)$.

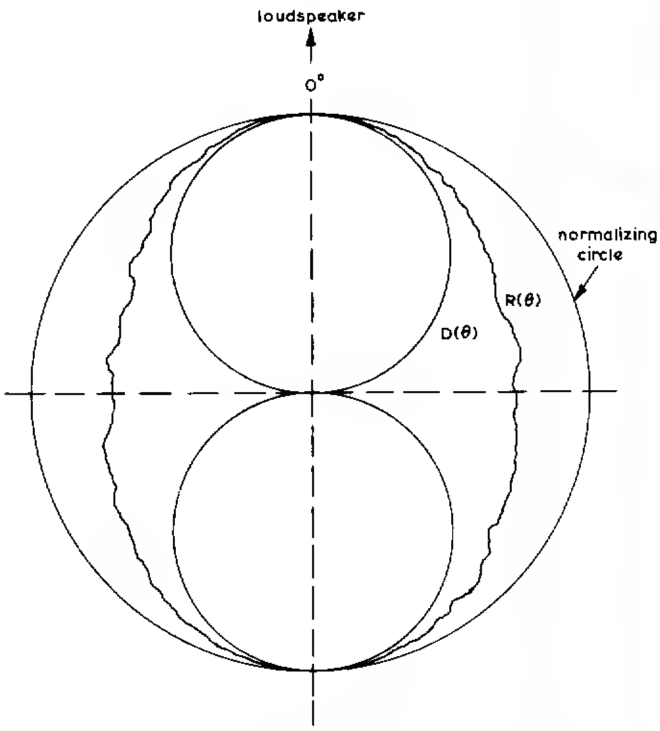


Fig. 8 - Furduev and Ch'eng T'ung differential-area polar-plot method

Note that for a completely diffuse sound field $R(\theta)$ would coincide with the circle and d would be unity. For a wave moving in one direction only, $R(\theta)$ and $D(\theta)$ would coincide making d zero. An attractive feature of Furduev and Ch'eng T'ung's index is that it is amenable to theoretical analysis; they were able to deduce some interesting results regarding the indices obtained from microphones having figure-of-eight and cardioid polar diagrams. After studying the results they obtained in large rooms, using such microphones, it was decided to apply the method to the six states of the experimental studio: the object was to compare the results so obtained with the values of P_c and S_A obtained earlier.

The rotating microphone turntable, an adapted gramophone turntable, is shown in Fig. 9. It was rotated at 0·75 r.p.m. in synchronism with a B and K Type 2305 level recorder fitted with a linear potentiometer.

A typical chart record is shown in Fig. 10. On examining the charts for condition F of the experimental studio, it was decided that the method was impracticable in the form described by Furduev and Ch'eng T'ung. It was found that the point on the chart corresponding to zero input to the recorder was not at the geometrical centre of the chart but on a circle at about 10% of full scale from the centre. It proved valueless to measure the requisite areas on the chart with a planimeter, as recommended, since the effect of the offset zero could not be corrected for in a simple way, i.e. the diagrams would not scale simply. It was also evident that to have ignored the offset would have resulted in large errors. It would have been possible to avoid this difficulty by plotting a linear chart rather than a circular chart, but values obtained in this way would not have corresponded to Furduev and Ch'eng T'ung's index.

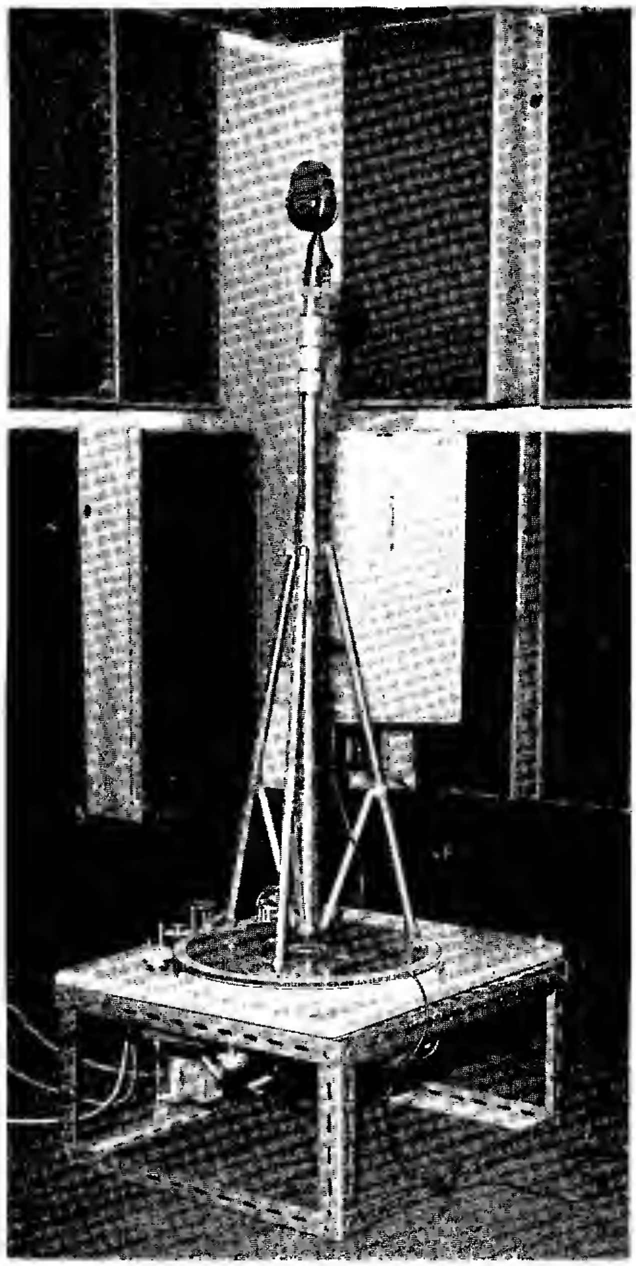


Fig. 9 - Rotating microphone turntable in experimental studio

It was also difficult to ensure that the forward response always corresponded to a fixed radius.

Improved results were obtained by using a digital form of microphone output using equipment previously developed.[5] The microphone output was amplified, rectified, sampled at ½° intervals, and the levels punched on eight-track paper-tape. The data was then processed in an

Elliott 803B computer according to a programme for calculating the requisite areas.

Measurements were made with octave-bandwidth noise at 250 Hz and 500 Hz, and with 1/3 octave-bandwidth noise at 1 kHz, 2 kHz and 4 kHz.

For each state of the room, two measurements were made at each of two microphone positions about 3·7 m from the loudspeaker. A PGS microphone (figure-of-eight) and a C12 microphone (cardioid) were both used. To get an overall picture, the values of d for the figure-of-eight and cardioid microphones at the frequencies 1 kHz, 2 kHz and 4 kHz were lumped together and the mean calculated for each condition; they are shown in Table 3.

TABLE 3

Room Condition	A	B	C	D	E
d	0·37	0·39	0·45	0·48	0·51

5. SIGNIFICANCE OF THE RESULTS

Fig. 11 shows a summary of the results by all three methods. The numbers in brackets next to the values of P_c and S_A describe the rank order of the room conditions, assessed, on the basis of increasing P_c and decreasing S_A.

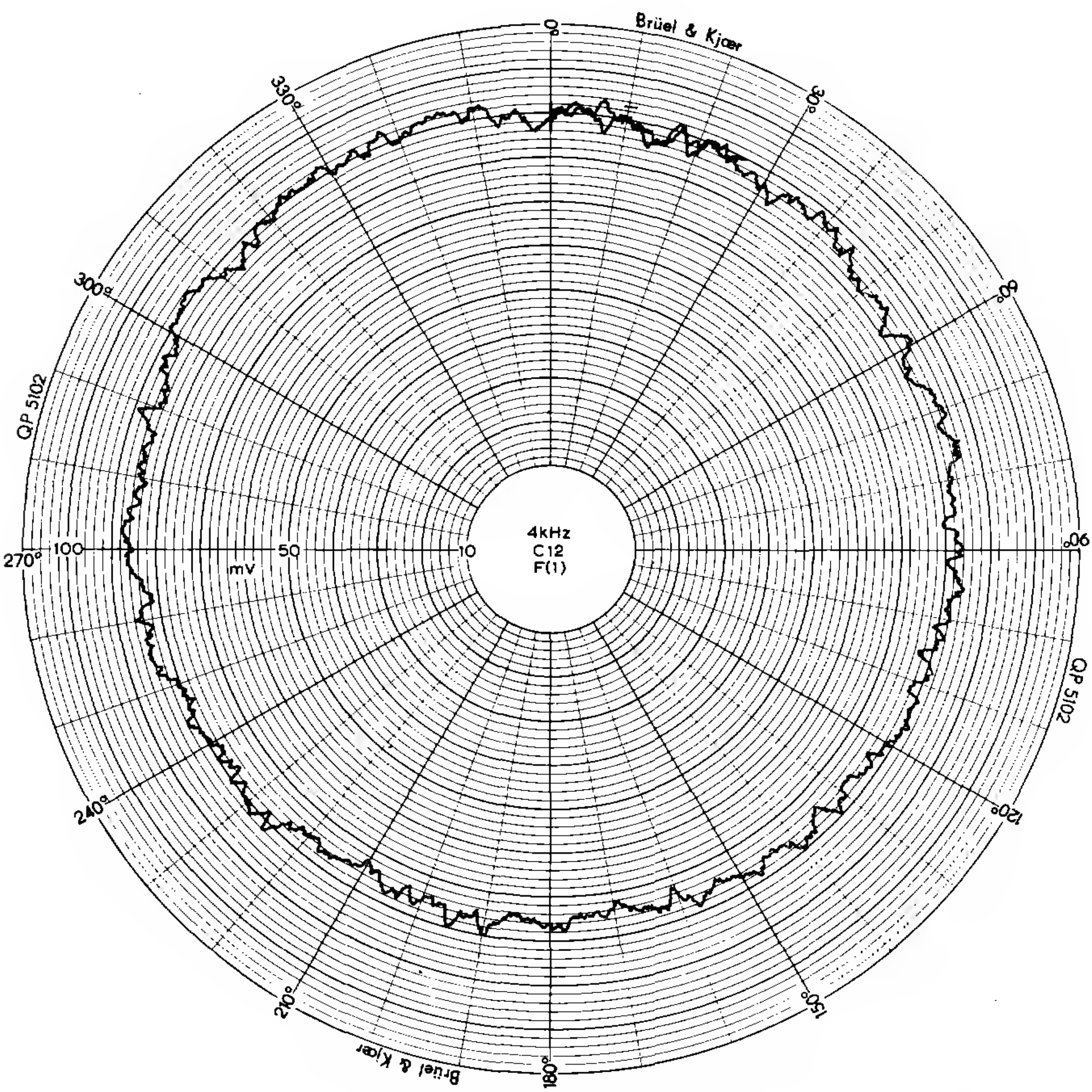


Fig. 10 - Typical polar graph of the output of a cardioid microphone at 4 kHz in the experimental studio

These two indices agree broadly in their assessments of the rank ordering of the states of diffusion of the room. The biggest discrepancy is in the rank order of condition C; experience suggests that P_c is the more accurate in this instance, as it ranks conditions B and D the least diffuse. These are the only two conditions in which one pair of opposite walls have absorption coefficients markedly different from the other two pairs.

It is difficult to assess the significance of differences in P_c because it is partly made up of errors in measurement of reverberation time. S_A does not suffer from this disadvantage; for the experimental studio, the standard deviation of S_A, from 1 kHz to 8 kHz, ranged from 0·03 to 0·15. Since there were ten measurements of S_A at each frequency the standard error of the mean of S_A varies between about 0·01 and 0·05.

The full value of P_c and S_A as diffusion indices can only be assessed after accumulating data and experience from a large number of rooms. Both indices have already been of some practical value, as was demonstrated when a reverberation test-recording from Studio 1 of the local-radio station at Leicester was processed. In the region around 400 Hz there was a marked increase in reverberation time, accompanied by a five-fold increase in standard deviation. The computer printout of Fig. 12 gives the corresponding values of S_A, and shows marked curvature of decays in the same frequency region. Later investigation showed that a resonating metal cabinet was responsible. The very low values of S_A obtained suggests that poor diffusion caused by the presence of undamped resonating objects may affect S_A much more than a poor distribution of absorbents.

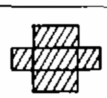
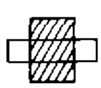
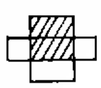
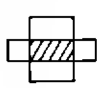
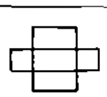
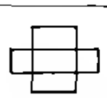
Room condition	Reverberation time at 500Hz (s)	P_C (%)	S_A	d
 A	0·32	14 (3rd)	0·93 (2nd)	0·37
 B	0·44	35 (6th)	0·85 (5th)	0·39
 C	0·52	16 (4th)	0·80 (6th)	0·45
 D	0·56	24 (5th)	0·87 (4th)	0·48
 E	0·82	8 (2nd)	0·89 (3rd)	0·51
 F No carpet	1·50	7 (1st)	0·96 (1st)	–

Fig. 11 - Comparison of the three indices of diffusion

S(A) FACTOR

FREQUENCY S(A) FACTOR

KR670926/1 LEICESTER STUDIO 1.
PROCESSED 27.9.67.
5 3.55 145 100 30 30 0.0

HZ	1	2	3	4	5	MEAN	S.D.
50	1.11	0.89	1.00	0.00	1.04	1.01	0.09
63	0.00	0.63	0.00	0.99	1.16	0.93	0.27
79	0.80	0.94	1.01	1.15	0.99	0.98	0.13
99	0.81	1.14	0.88	0.68	0.73	0.85	0.18
125	0.65	0.85	0.57	1.08	0.98	0.83	0.21
157	0.76	0.70	0.82	0.71	0.55	0.71	0.10
198	0.87	0.90	1.18	0.85	0.76	0.91	0.16
250	0.75	0.81	0.87	0.87	1.00	0.86	0.09
315	0.82	0.48	0.73	0.46	0.92	0.68	0.20
397	0.65	0.56	0.93	0.75	0.43	0.66	0.19
500	0.76	0.70	0.43	0.54	0.59	0.60	0.13
630	0.86	0.87	0.88	0.94	1.09	0.93	0.09
794	0.88	0.91	0.83	1.00	0.91	0.91	0.06
1000	1.05	0.76	1.02	0.69	0.93	0.89	0.16
1260	0.87	0.66	0.63	0.83	0.68	0.73	0.11
1587	0.89	0.95	0.92	0.86	0.85	0.90	0.04
2000	0.90	0.85	1.05	0.82	0.93	0.91	0.09
2520	1.04	0.91	1.03	0.94	0.92	0.97	0.06
3175	0.87	1.02	0.96	0.91	0.90	0.93	0.06
4000	0.85	1.03	1.01	0.90	0.91	0.94	0.08
5040	0.77	0.85	0.83	0.93	0.92	0.86	0.06
6350	0.84	0.81	0.92	0.83	0.83	0.85	0.04
8000	0.86	0.81	0.90	0.90	0.00	0.87	0.04

Fig. 12 - Printout of S_A for Studio 1, Leicester

From Fig. 11 it is clear that the index d is of no value for small rooms of moderate absorption, since it increases with increase in reverberation time. It seems that in such rooms it is impossible to get far enough from the direct (and hence non-diffuse) sound from the source. The effect of this is simply to override any contributions from the directional characteristics of the reverberant sound field. The greater the absorption in the room, the smaller is the contribution from the reverberant sound. It is possible to argue that in general the more reverberant room is *ipso facto* more diffuse, but diffusion indices based on this view are not of very great value because they do not correspond to subjective judgements of the effects due to the poor distribution of absorbents.

An attempt was made to separate the contribution of the reverberant field by assuming a relation of the form:

$$d = b_0 + b_1.T + b_2P_c + b_3S_A$$

where the b's are constants and T is the reverberation time.

The sets of values of d, T, P_c and S_A were run in the Elliott 803B computer with a programme designed to determine the influence of each of the variables.* The value of b_1 obtained was significantly positive, but the values of b_2 and b_3 were not significantly different from zero. The attempt therefore failed, but of course the result does not exclude the possibility of relations other than the linear one postulated above.

6. CONCLUSIONS AND RECOMMENDATIONS

Modifications have been made to the diffusion indices of Randall and Ward,[1] P and S, to make them suitable for derivation from computer analysis of reverberation test-recordings.

The new parameters, P_c and S_A, like the old, depend on the variation of reverberation time with position and the curvature of decay curves, respectively. P_c and S_A also have been shown to be dependent on the state of distribution of absorbents. They can be obtained very easily from the computer analysis of reverberation test-recordings with little extra expenditure of time and effort. Their full significance will only be realized when they have been determined for a sufficient number of operational studios. It is recommended, therefore, that P_c and S_A be determined and noted whenever reverberation test-recordings are made.

A diffusion index due to Furduev and Ch'eng T'ung, which is based on the measurement of areas of polar diagrams obtained with a directional microphone, is found to be of no value in small rooms of moderate absorption.

* Library programme S.101, 'Multiple Regression'.

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